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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL
LABORATORY, HARVARD UNIVERSITY.

THE TECHNIQUE OF HIGH PRESSURE EXPERIMENTING.

BY P. W. BRIDGMAN.

Presented, Jan. 14, 1914. Received, Dec. 29, 1913.

IN this paper I propose to collect the results of several years' experience in designing apparatus and conducting experiments at high pressures. The rather unusual magnitude of the pressures, from 12000 to 30000 kgm / cm², has made necessary the development of methods different from those which have hitherto sufficed for more moderate pressures, up to perhaps 3000 kgm/cm². I shall endeavor to present enough of the details of manipulation so that any one may construct apparatus for experimenting in this as yet almost untouched field of higher pressures. It is not claimed that the methods presented furnish the only solution of the problems of high pressure technique; all that is claimed is that the methods given are possible solutions which have stood the test of constant use for a number of years.

The plan of presentation is to indicate the essential parts of a piece of high pressure apparatus, and then to describe in detail the peculiar features of construction of each of the parts.

The apparatus consists essentially of a chamber in which pressure is produced by a plunger, a mechanism for pushing the plunger into the chamber, a tube connecting the chamber in which pressure is produced with a second chamber adapted to the particular investigation, and a pressure gauge. The second chamber is the only part of the apparatus that need be varied for different experiments. The other parts will be described in detail here.

PACKING.

Obviously an absolute essential to the success of any high pressure apparatus is some reliable method of packing. I shall describe here the broad principle of this packing, leaving for further description the numerous modifications for special uses. All the packing used in this work is so designed that at high pressures it is made tighter by the action of the pressure itself. Figure 1, showing the

packing for the piston will make the principle clear. The piston P pushes the plug A through the medium of the hardened ring R, the cupped washer of soft steel, C, and the rubber packing B. The liquid compressed is below A at L. The plug A is provided with a stem which is long enough to reach into the ring R, but not long enough to reach to the piston P. If now we consider the equilibrium of A, we see that the fluid pressure over the lower end of A must be balanced by the pressure exerted by the packing B on an area less than that of A by the area of the unsupported stem. The result is that the hydrostatic pressure in the packing B per unit area is always a certain percentage higher than that in the liquid, so that the liquid can

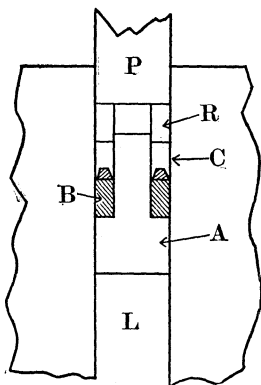


Fig. 1.

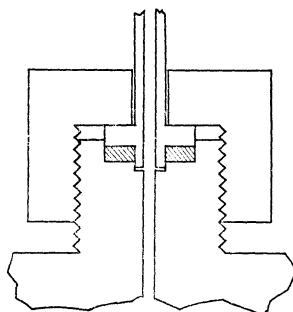


Fig. 2.

FIGURE 1. Shows the general principle of the packing by which the pressure in the packing B is always kept higher than that in the liquid at L. The scale of the diagram is $\frac{3}{4}$ actual size.

FIGURE 2. Shows a common previous type of packing for high pressures. The packing is compressed by a powerful screw into a confined space. This packing leaks when the pressure in the liquid rises as high as that initially applied with the screw.

never leak past the piston. This principle is capable of manifold modification and adaptation, but it will always be found that there is somewhere an area unexposed to the action of pressure, so that the hydrostatic pressure in the packing itself is always higher than that in the liquid.

It is instructive to compare this packing with that formerly used for high pressures, by Amagat, for instance, up to 3000 kgm. His packing is compressed initially by a powerful screw into a confined

space. Reference to Figure 2 will show that such a packing must leak as soon as the pressure in the liquid reaches the pressure applied initially to the packing by the screw.

We proceed to the detailed consideration of the various parts of the apparatus.

THE MECHANISM FOR MOVING THE PISTON.

This mechanism, of course, may be anything that will furnish a force of the required intensity and exert it over a long enough distance. It has been usual in previous high pressure work to use a screw to drive the piston. When the pressure to be produced becomes high, the screw becomes very inefficient, and it is highly desirable to replace it with a hydraulic press. In my early work up to 6000 kgm., the piston ($\frac{1}{2}$ inch in diameter) was driven by a screw. This screw had a pitch of 8 threads to the inch, and needed a six foot wrench to turn it. Its efficiency was less than 5%. Furthermore, even when made of nickel steel, the screws, which were one inch in diameter, finally broke down and had to be replaced. The hydraulic press which I have been using for the last six years has never given the slightest trouble. To avoid bulky apparatus, it is desirable to actuate the press with liquid at a fairly high pressure. For this purpose a pump of the Société Genevoise is convenient, giving 1000 kgm/cm² with a lever. The diameter of the piston of the hydraulic press is $2\frac{1}{2}$ inches, which permits, therefore, of a pressure of 25000 kgm/cm² on a $\frac{1}{2}$ inch piston, the size usually used. The barrel of the press is made of mild steel, 4 inches in outside diameter. The piston is threaded over the entire length and provided with a heavy nut by which the piston may be maintained in any desired position, even when the pressure on the low end is relieved. This arrangement has proved an indispensable convenience in operation. Opposed to the main hydraulic press is a smaller press with a $\frac{3}{4}$ inch piston, connected to the larger piston by tie rods and a yoke pressing against the nut. By this auxiliary press the piston of the large press can be rapidly returned to its initial position after completion of a stroke.

It is essential that the press be accurately constructed so that the thrust on the high pressure piston shall be exactly centered; otherwise the piston will buckle.

The packing on the low pressure piston of the press embodies the principle shown above. It might be possible to use a cup leather,

but this would probably last for only a short time, for my experience has been that even so low a pressure as 1000 kgm. is sufficient to

rapidly mechanically disintegrate the fibrous structure of the leather. Figure 3 shows the packing. The end piece A with stem B plays in the hole C in the end of the piston P. The packing is a disc of $\frac{1}{4}$ inch soft rubber between two washers of $\frac{1}{8}$ inch red fibre. The rubber washers will wear away in time, but the fibre washers will have then become so adapted as to give the necessary tightness. In six years of constant use, this packing has been renewed only once, and then only as a matter of precaution, when the press was dismantled for another purpose. In order to make absolutely sure that the end of the stem B is always free from stress it is well to drill a small lateral hole at the bottom of C to allow any liquid to flow away that might

percolate around the packing when it is relaxed, as it is when there is no pressure behind it.

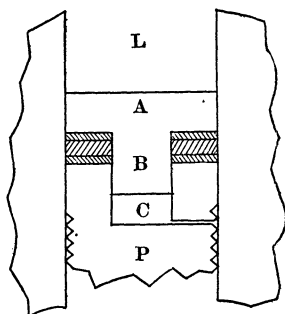


FIGURE 3. Shows a section of the cylinder of the hydraulic press with the packing on the end of the piston P. Pressure up to 1000 kgm. per sq. cm. is exerted on the piston by means of a liquid at L. The scale of the diagram is $\frac{1}{3}$ actual size.

THE HIGH PRESSURE PISTON.

It has been found best to make this in two distinct parts; a piston proper by which pressure is transmitted from the press, and a packing plug driven by the piston into the cylinder. The piston proper is a cylindrical piece of steel with perfectly plane ends. It is made of tool steel, first turned between centers to the approximate dimensions, then hardened glass hard and left with the temper undrawn, ground to the final size between centers, and finally the center marks ground out, leaving the ends plane. If the center holes are not ground out, the piston is much more likely to crack. For pressures up to 15000 kgm. any high grade of carbon tool steel is good enough. For higher pressures it will be well to use one of the special tool steels that admit of being made especially hard. I have found chrome or silicon steels very suitable. One of these broke at 50,000 kgm/cm². It has been

my experience that the new high speed steels are not so good for this purpose as the old fashion carbon steels. It is the hardness that counts — and brittleness is no disadvantage. After prolonged use, the pistons may be expected to show longitudinal cracks. I have never had a piston fail in actual use, although I have used pistons a number of times after the appearance of the cracks. The piston must not be too long, or it will buckle. About 4 inches is a good length for a diameter of $\frac{1}{2}$ inch. In use, of course, the piston is partially supported by the cylinder when high pressures are reached. A cylinder $\frac{1}{2}$ inch in diameter may easily support 25000 kgm. with an unsupported length of $1\frac{1}{2}$ inches, provided that it is properly centered.

Some sort of face plate must intervene between the hardened piston and the soft steel piston of the press. The form shown in Figure 4 is convenient. This is made of tool steel, hardened, and drawn to a blue. If not drawn, it is quite likely that it will crack, or even that

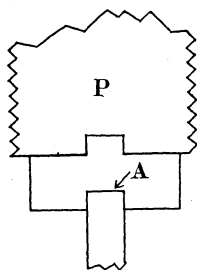


Fig. 4.

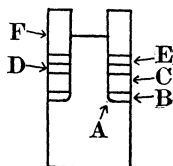


Fig. 5.

FIGURE 4. Shows the face plate of hardened steel between the half inch high pressure piston and the piston of soft steel, P, of the hydraulic press. The scale of the diagram is $\frac{2}{3}$ actual size.

FIGURE 5. The packing plug on the movable piston for use up to the highest pressures in the finally seasoned apparatus. The scale of the diagram is $\frac{4}{5}$ actual size.

the center will be sheared through. A thin (0.01 inch) copper washer at A ensures uniform seating of the piston. The piston, it may be mentioned, is most likely to crack longitudinally when the ends press against something soft that may flow out laterally, carrying the piston with it by friction. It is well, therefore, to make the center hole in the face plate a good fit for the piston.

The principle of the packing plug at the end of the piston has been described, but there are a number of details of construction. This plug may have two forms, one for use in the apparatus as finally set

up ready for experiment, the other for use in giving the preliminary seasoning. I describe first the plug for regular use. Figure 5 shows the dimensions. It is particularly important that the corners at A should be left slightly rounded. The plug may be made an easy fit, say 0.001 of an inch too small, for the hole in the cylinder. The plug is further provided with a washer of copper, B, $\frac{1}{16}$ of an inch thick, a force fit for the hole. For convenience in handling, it is well to solder the washer B to the plug. Above B is the packing washer, C. $\frac{1}{8}$ of an inch is thick enough for this rubber washer if only a few strokes of the piston are to be made, but since the enormous friction rapidly wears away the rubber, the packing should be made thicker if longer use is contemplated. It is an advantage to keep the packing as thin as possible, for in this way the total friction is reduced. Above the packing is another copper washer, D, identical with the lower one, and above this a washer, E, of the same dimensions, of soft Chrome Nickel steel. Finally, above the soft steel washer, is a hardened steel ring, F, against which the piston bears. This ring is likely to crack. If pressures not over 12000 kgm. are to be used, the ring may be made of tool steel, hardened, and drawn to a black. But if pressures to 25000 are to be used, the ring must be left glass hard, and one may expect to renew this ring with each new setting up of the apparatus.

The packing plug just described is one of the few parts of the apparatus almost certain to give way after long use. Fortunately the results of failure are nothing more serious than the projection of the severed stem against the piston, and sometimes, though not usually, leak. Failure takes the form of separation of the stem from the head at the corner A by the "pinching-off"¹ effect. The grade of steel used for the plug is therefore, important; a peculiar sort of toughness is necessary. I have found best for this a Krupp Chrome Nickel steel, grade E. F. 60.0. The New York agents are Thos. Prosser and Son, 15 Gold St. It is strange that another grade of steel with a higher tensile strength, and better adapted for the construction of the cylinders, is not so good for the plug. The plug is to be hardened in oil, and the temper left undrawn. The degree of heating during the hardening is important, slight differences having a great effect on the resistance to the "pinching-off" effect. The precise temperature of heating can best be told by experiment.

The size of the rubber washers used for packing is also important; these should be as much larger than the hole as can conveniently be

¹ P. W. Bridgman, *Phil. Mag.*, **24**, 68 (1912).

used. The reason is that under high pressure rubber becomes rigid and brittle like glass, and under the right conditions may even crack. If the rubber is initially so small that under the high pressure its natural volume compression would make it smaller than the hole, then it would certainly leak if it were not for the excess pressure in the packing over that in the liquid. But the rigidity of the rubber may become so great that the excess pressure is not sufficient to force it tightly against the walls of the cylinder, unless the rubber would of itself completely fill the hole at the high pressure.

The form of plug to be used during the preliminary seasoning of the apparatus is essentially the form described above so modified as to allow it to follow the stretching of the cylinder. It could be used under all circumstances, except that the friction is considerably higher than that of the other form. It is shown in Figure 6. The possibility of distension of the head to follow the stretching of the cylinder is provided by a coned ring of copper, A, backed with solder, B, and the possibility of stretching at the upper end is provided by using a washer of soft steel, C, rather deeply cupped, the groove of the cup being filled with a solder. With such a plug, a pressure of 25000 kgm/cm.² may be maintained in a cylinder which has stretched $\frac{1}{16}$ of an inch.

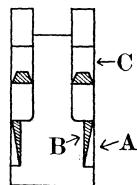


FIGURE 6. Piston packing for high pressures for use in seasoning the cylinders when provision must be made for stretch of the cylinder without leak. The scale of the diagram is $\frac{1}{4}$ actual size.

THE CYLINDERS.

The cylinders, or "bombs," need to be subjected to a seasoning process, because the pressures at which they are to be used are beyond the natural elastic limit of the steel. It is, therefore, necessary to raise the elastic limit by the application of a stress beyond the original elastic limit. But since the application of a stress great enough to permanently raise the elastic limit produces a permanent distortion of the cylinder, the cylinder must be machined again to the final size after the preliminary stretching.

The choice of steel for the cylinder is a matter of much importance. A high tensile strength, combined with a moderate elongation before rupture is essential. The Krupp Chrome Nickel steel mentioned for the piston is satisfactory for this purpose, or somewhat better is a

Chrome Vanadium steel, "Type D," made by the Halcombe Steel Co. of Syracuse, N. Y. This latter steel may show a tensile strength as high as 300,000 lb. per sq. in. Before the stretching process, the cylinder should be hardened by heating to from 870° to 1000° , and quenching in oil. The temper should not be drawn at all after this hardening. It is not possible to get either of these two steels glass hard like tool steel, unless by case hardening, so that it is possible to enlarge a hole by reaming in a piece of steel so hardened, or even to drill it.

The dimensions of the cylinders are capable of some variation. It has been my experience that the outside diameter of the cylinder should be from six to ten times that of the inside hole. Not much is gained by making it heavier than ten times, and it is likely to break if made much less than six times. Several cylinders of four times the diameter have eventually broken at 12000 kgm. although they withstood a seasoning pressure of 25000 kgm. Choice of dimensions must furthermore be influenced by the consideration that there is a distinct advantage in keeping the absolute dimensions of the apparatus small, because hardening by quenching cannot reach to the interior of a large piece of steel. I have found it convenient to use a diameter of about $\frac{1}{2}$ of an inch for the piston, and an outside diameter for the cylinder of from 4 to $4\frac{1}{2}$ inches. If the chrome vanadium steel is used, the hole may be made initially $\frac{1}{2}$ inch in diameter, and the stretch after seasoning to 25000 kgm. will be small enough so that the hole may be reamed to a final size of $\frac{17}{32}$ of an inch. If the Krupp steel is used, a slightly greater allowance for stretch must be made, but it will still be less than $\frac{1}{16}$ of an inch on a diameter of $\frac{1}{2}$ an inch.

The actual details of the seasoning require little comment. Pressure should be increased gradually, stopping after every increase long enough for the viscous yield to entirely disappear. The length of the steps by which the pressure is increased may be so chosen that the maximum is reached in from ten to fifteen steps. Pressure should be maintained at the maximum for several hours. One application of the seasoning pressure is sufficient, unless the stretch should be so great as to make a second stroke necessary to reach the maximum pressure. The seasoning pressure should be as high as can be reached without permanent deterioration of the steel. With the grades of steel mentioned above, this pressure may be safely as high as 25000 to 30000 kgm. A mixture of $\frac{2}{3}$ (by volume) glycerine and $\frac{1}{3}$ water is suitable for transmitting the pressure during the seasoning. The necessary length of stroke may be reduced by filling those parts of the

interior of the cylinder which will not be reached by the piston with a core of brass or steel, thus reducing the volume and the compression of the liquid.

One must always be prepared for disappointment after constructing one of these cylinders, for in spite of the greatest care of the manufacturer one cannot at the present day be sure that the steel will be free from flaws. These flaws may develop during the preliminary seasoning, but are much more likely not to show themselves until the piece has been reamed to the final size. For example, one cylinder had been used for a year before finally a seam opened in a wall $2\frac{1}{2}$ inches thick, letting through a very fine stream of liquid. It is a matter of pure chance whether a flaw will be found or not; of two pieces from the same bar, one may have a flaw, and the other may be sound. It has been my experience that about three out of every four pieces are sound.

CONNECTING PIPES.

The proper construction of connections from one piece of apparatus to another has been until recently the most serious problem of all this high pressure work, and the cause of almost every explosion. The problem has at last, however, been satisfactorily solved. Different types of connection may be used, depending on the pressure to be carried. We begin with the connections for the lower pressures.

For low pressure transmission, such as for the low pressure end of the press up to 1000 kgm., the most convenient connection is copper tubing. The size I have used is $\frac{1}{4}$ of an inch outside diameter and $\frac{1}{16}$ of an inch inside diameter. This may be used either in its hard drawn state or else annealed. It will stand a single application of 1500 kgm. and may be used almost indefinitely to 1000 kgm. For coupling together two pieces of pipe, a cone coupling with right and left handed thread will be found very convenient. (See Figure 7.) The hollow cone may be best made of steel, since it is subjected to greater strain than the other, which may be made of brass. The copper tubing is attached to the cones by threading and soldering. The thread may well be as long as $\frac{1}{2}$ inch, and the unthreaded part another $\frac{1}{2}$ inch. If the soldered length at the end of the pipe is much less than 1 inch long, solder will be slowly extruded through the threads by the pressure, and there will eventually be leak.

For making connections to the cylinder the coupling shown in

Figure 8 is useful. It will be seen that this is an application of the packing principle described above. Here the projecting pipe itself is the area unsupported, so that the rubber packing, A, exerts its pressure on an area less than that acted on by the liquid by an amount equal to the area of the cross section of the pipe. Brass washers, B and C, are strong enough for the end of the tube. These brass washers should fit the hole within one or two thousandths of an inch,

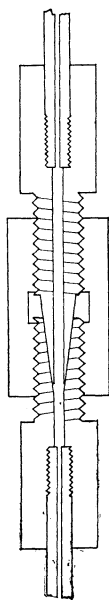


Fig. 7.

FIGURE 7. Coned coupling for copper tubing up to 1000 kgm. The scale of the diagram is $\frac{1}{2}$ actual size.

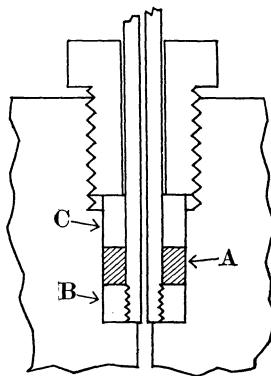


Fig. 8.

FIGURE 8. The packing for copper tubing, or, with slight modifications, for commercial steel tubing up to 4000 kgm. The scale of the diagram is $\frac{2}{3}$ actual size.

so that the rubber may not be blown through the cracks. Occasionally, after several years' use, a copper tube may fail by the "pinching-off" effect at the rubber packing.

For pressures higher than 1000, up to 6000 or 7000 kgm., it is possible to get commercial steel tubing. The National Tubing Co., Pittsburgh, Pa., draws a size of "Shelby" tubing $\frac{5}{16}$ of an inch outside diameter, and $\frac{1}{16}$ of an inch inside diameter, which I have found suit-

able. This may stand as much as 9000 kgm. on the first application of pressure. The tubing should not be softened, but left hard drawn. It is likely to have flaws in it, but these can be usually detected by a careful examination of the outside of the tubing. For pressures up to 4000 kgm. it is safe to use with this tubing a connection like that shown above (in Figure 8) for the copper tubing. But the right and left hand thread connection (of Figure 7) cannot be used, since for one thing a soldered joint will not stand the pressure, the solder being eventually pushed out. The washers, of course, should be of steel, and it pays to cup the upper steel washer, filling the groove of the cup with solder. At pressures in excess of 4000 kgm. the tube is likely to fail by the "pinching-off" effect, if the rubber type of packing is used. This "pinching-off" effect almost invariably takes place at the bottom of the thread, the weakest part of the tube.

For higher pressures than 4000, up to 6000 or 7000, a connection must be used which prevents the packing from coming into contact with the thread. The cone packing of Figure 9 answers this purpose. The cone, A, screwing over the end of the tube is of hardened nickel steel. The liquid is kept from coming into contact with the thread by a ring, B, of soft steel, protected by solder, C, above. A hollow cone of soft steel, D, cut at a slightly more acute angle than the solid cone is the packing. To ensure initial tightness, before pressure has been pushed high enough to make the cones conform to each other, a thin piece of rubber, or a ring of copper may be placed between the cones. This packing has never been quite satisfactory, since often rupture did ultimately occur at the base of the threads. At the Geophysical Laboratory in Washington a method has been developed by Dr. John Johnston for packing commercial steel tubing that will doubtless be found more convenient than the above.² He has tested the method to 8000 kgm., but whether the tubing will stand the continued application of 8000 I do not know.

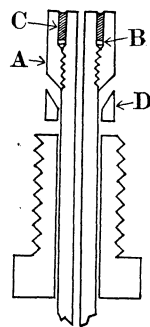


FIGURE 9. Coned packing for use with tubing up to 7000 kgm. The purpose is to keep the pressure from the threads on the outside of the tubing, where rupture is particularly likely to occur. The scale of the diagram is $\frac{2}{3}$ actual size.

For continued use to pressures higher than 7000 I have not been

² John Johnston and L. H. Adams, Amer. Jour. Sci., **31**, 505 (1911).

able to use any commercial drawn tubing, but have found it necessary to drill the tubing from the solid rod. The same grade of steel as that used for the cylinders should be used for the drilled tubing. The inside diameter of the tubing is $\frac{1}{16}$ of an inch, and it is quite possible with a little practise to drill pieces at least 17 inches long. The drill should be cut on the end of a long piece of drill rod; it does not pay to try to braze a long shank onto a short drill. Two essentials in successfully drilling a long piece of tube are to start with the drill accurately central, and to use as homogeneous stock as possible. The drill need not be expected to run more than $\frac{1}{2}$ of an inch out of center on a piece 17 inches long. After getting the drill accurately started for two or three inches it will be found convenient to put the drill in a hand tool holder and force it in by hand. This arrangement makes it much simpler to run the drill in and out of the hole to remove chips. Great care must be observed that the drill does not become clogged with chips. I have found that it pays to carefully clean out the hole with a swab after drilling not more than $\frac{1}{8}$ of an inch. It is easy, if all precautions are observed, to drill a hole $\frac{1}{16}$ of an inch in diameter 17 inches long in from seven to eight hours.

After drilling, the rod is to be turned off over the hole to the final size, so that the whole may be concentric, and then hardened in oil and left undrawn, exactly as are the cylinders.

The problem of the proper connections at the end of the pipe is one that has given great trouble. The coned connection described above was used for some time. The only change necessary from the form used for lower pressures is the interposition of a hardened steel washer between the soft cupped washer and the retaining screw. I have successfully reached 12000 kgm. a number of times with this packing, but ultimately rupture always occurred at the bottom of the threads. It may be that rupture at this point is not a pure pressure effect, but that the cylinders are too heavy for the tubing, so that there is some slight bending at the thread under the unavoidable hard handling of setting up the apparatus. Be that as it may, the cone packing is unsatisfactory for long continued service, particularly at temperatures much above that of the room.

The packing for the connecting tube finally adopted, and which has proved entirely satisfactory, is shown in Figure 10. The main improvement of this over the cone form is that it leaves the tube much heavier, the minimum outside diameter at a point exposed only to internal pressure being $\frac{3}{4}$ of an inch in the new form against about $\frac{1}{4}$ of an inch at the bottom of the thread in the cone form. The end of

the tube has a heavy thread cut on it, and is provided with a milled head, H, for a wrench. The packing is composed of three rings; a thin ring of Bessemer, A, a ring of lead, B, $\frac{1}{16}$ of an inch square in cross section, and a ring of Bessemer, C, of $\frac{1}{16}$ inch square section. These rings fit over the end of the tube in an annular space $\frac{1}{16}$ of an inch wide between the tube and the walls of the cylinder. On screwing up the the tube, the rings are forced against a conical shoulder, D, on the tube. It will be noticed that the Bessemer ring C supports the hydrostatic pressure over the entire area of one face, but that at the rear face there is a vacant space, E, so that the pressure must be balanced by the force exerted by the cone on the *corner* of the ring. This means that the intensity of pressure in the steel at the corner is much greater than the pressure in the liquid, so that leak cannot occur. Here again, we have the principle of a packing with an unsupported area. Tightness at the outside of the Bessemer ring is secured by the stretching of the ring over the cone.

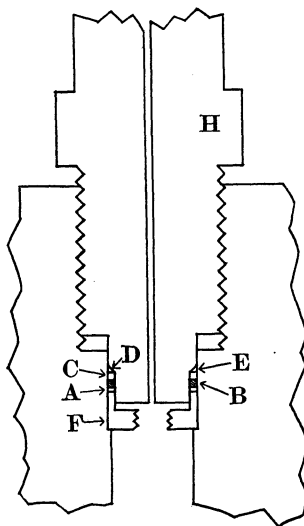


FIGURE 10. Detail of the final packing of rings of soft steel for the drilled tubing of nickel steel. The scale of the diagram is $\frac{2}{3}$ actual size.

The lead washer merely serves the purpose of giving initial tightness, and the thin Bessemer washer is to keep the lead washer in place. The projecting ledge against which the washers bear opposite the cone is shown in the figure as the rim of a nickel steel cup, F, resting loosely in the hole. This construction is convenient, because it provides a way of withdrawing the packing rings after use by inserting a threaded rod through the bottom of the cup and pulling the cup out. It is, however, quite possible to use part of the cylinder itself as the ledge, since the removal of the washers, even without the device of the cup, does not present serious difficulties. The lead ring and the heavy Bessemer ring cannot be used more than once, but the thin Bessemer ring for retaining the lead may be used several times.

This packing has, at the date of writing, been in continuous use for nearly a year, up to 13000 kgm. and 200°, without a single rupture or

leak of any kind. It has not been tested higher, but there is no reason why it should not hold until the steel cylinder stretches enough to leak. It is a satisfaction in using this connection to feel that this part of the apparatus is at least no weaker than any other.

THE PRESSURE GAUGE.

Without doubt the most convenient means of measuring high pressure is to measure the change produced by the pressure in the electrical resistance of some such alloy as manganin. The details have been given in a previous paper.³ The only structural difficulties

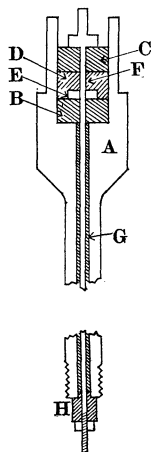


FIGURE 11. The insulating plug for leading electrical connections to the interior of the pressure chamber. The scale of the diagram is $\frac{2}{3}$ actual size.

with the method are those incidental to getting electrically insulated leads into the cylinder. The principle of the insulating plug has also been described in a previous paper, but not in much detail, and since several improvements have been introduced, it will pay to redescribe it. The plug is shown in Figure 11. It consists essentially of an outer shell, A, to which one electrode is silver soldered, and running through it and insulated from it, a thin steel stem, F, which forms the other electrode. The outer shell of the plug, A, is made of Krupp Chrome Nickel steel, hardened in oil. The packing of the shell used at present is soft rubber, after the same design as that used for the tubing at lower pressures. This packing is not shown in the diagram. There is no weakening of the plug here by a thread on the outside, so that the "pinching-off" effect is not nearly so troublesome as in the case of the packing for the tubing. Moreover, by making the shell with a taper shoulder, and placing over this a soft steel cone, against which the rubber bears, thus providing for the possibility of slip of one metal part over the other in the locality where the "pinching-off" effect would be most likely to occur if the metal were of one solid piece, and by using rubber washers only $\frac{1}{8}$ of an inch thick, the danger of "pinching-off" is reduced to a minimum. However, this design

³ P. W. Bridgman, These Proceedings, **47**, 321-343 (1911).

does not entirely do away with the effect; it is safe to count on a rupture about once a year if the apparatus is used continually to 12000 kgm. Failure of the plug need not result in complete rupture. Once or twice I have been troubled with an obscure leak which I finally traced to a crack at the base of the cone of A, where the "pinching-off" effect might be expected to occur. If ever occasion should arise to make new plugs, I intend to redesign them so as to use the ring packing of steel now used for the connecting tubes.

The insulating properties of the plug are provided by two layers of mica washers, B and C, turned (not punched) so as to be a force fit for the hole. Tightness against leak is provided by a layer of rubber, D, between the two layers of mica. The fine stem, F, is insulated from A for the rest of its length by a thin glass tube, G, slipping into the annular space between F and A. A small cylinder of hard rubber, H, at the outer end completes the insulation. The insulating properties of the plug are improved if all the parts are dipped into paraffine heated to from 120° to 140° immediately before assembling, and if they are kept hot enough during the assembling so that the paraffine remains melted. The insulation resistance is at least 100 megohms, the limit of the measuring instrument used.

It will be noticed that the insulating packing uses again the principle of the unsupported area, the central stem in this case being the unsupported part. But the area of the stem is so slight that the excess pressure provided by it may not be sufficient to overcome the friction in the mica washers against the side of the plug. It is therefore necessary to make the rubber washer initially considerably larger than the hole, or else the tightness will not be permanent. A washer initially $\frac{17}{32}$ of an inch to go into a hole $\frac{7}{16}$ of an inch in diameter is not too large.

The steel disc at E is necessary to prevent the rubber blowing out past the mica washers along the stem. This disc should be of hardened nickel steel. The stem F passing through the washers is also of hardened nickel steel. It, together with the head at its upper end, must be made from one piece. Attempts to braze or screw the head onto a piece of wire have uniformly failed. This thin stem is also likely to fail by the "pinching-off" effect, where it passes through the rubber, or if the friction of the washers is too great, it may be torn apart by the tension afforded by the expansion of the washers during decreasing pressure. Several times I have observed rupture from this cause at 6000 kgm. after decreasing pressure from a maximum of 12000.

The pressure of 6000 kgm. is still sufficient to project the fine stem with considerable violence after rupture takes place, so that one must be particularly careful not to yield to a false feeling of security in handling the plug during decreasing pressure. The insulating plug as thus constructed is at present the part of the apparatus most likely to fail. The mica washers eventually fail along a cone of shear reaching from the hardened disc to the hole in the stem. Slipping of the mica on the shear planes is likely to be accompanied by unsymmetrical yielding of the rubber and the hardened disc, so that the fine stem may be bent or even sheared off by the tilted disc.

It would probably pay in designing new apparatus to experiment with a form of insulating plug developed at the Geophysical Laboratory.⁴ Soapstone instead of mica is the insulating material, and the rubber washer is dispensed with, so that it is simpler in construction. It has not been tested over so wide a range as the form described above, but has given perfect satisfaction up to 8000 kgm. The form described above has been used to 21000 kgm., although it would not stand this many times.

VALVES.

I have as yet not been able to construct satisfactory valves. However, it may be worth while to describe a substitute which has been found useful for one particular purpose. In the absence of valves the desired final pressure must be reached with one stroke of the piston. But if the apparatus connected to the cylinder is of more than two or three times the capacity of the cylinder itself, it will not be possible to do this because of the compressibility of the transmitting liquid. But since the greater part of the compression of a liquid occurs in the first few thousand kilograms, it would in many cases be sufficient if an initial pressure of a few thousand kilograms could be produced in the cylinder before the stroke begins. This is accomplished by the use of a small by-pass at the upper end of the cylinder, so situated that it is just uncovered when the piston is withdrawn to its extreme position. Initial pressure to the desired amount is produced in the apparatus by an auxiliary pump through the by-pass, which is then cut off by the descent of the piston. It is necessary to make this by-pass very minute, so that the rubber packing of the piston may not be blown out through it as the piston passes by. One convenient way of doing this

⁴ John Johnston and L. H. Adams, *Amer. Jour. Sci.*, **31**, 507 (1911).

is to drill and tap a convenient sized hole at the upper end of the cylinder, say for a 10-32 thread, $\frac{1}{4}$ of an inch long, and then to screw tightly into the tapped hole a carefully cut screw, across the threads of which (that is, parallel to the axis) a fine scratch has been made. This scratch is the channel by which the transmitting fluid gains access to the interior of the cylinder; its size may be regulated at pleasure by varying the size of the scratch. The screw may be made of soft tool steel, since the pressure it has to withstand is not high, thus permitting the end projecting into the cylinder to be reamed off.

The use of a by-pass necessitates the use of an auxiliary pump giving several thousand kilograms. I have found it convenient to use a second pump of the Geneva type, coupled to an intensifier of readily suggested design, stepping up the pressure four times.

PLUGS.

In adapting pieces of apparatus to new uses it will often be necessary to plug holes previously used for connections. This may be done with a plug packed according to the simple method of rubber washers used for the connecting pipes at low pressures (see Figure 12). If the stem and the head, A, are turned from one piece of Krupp Chrome Nickel steel and hardened, the "pinching-off" effect will seldom be troublesome. One should realize, however, that the "pinching-off" effect is treacherous, and likely to come at the most unexpected times. All parts liable to this effect should either be shielded, or else they should be pointed in such a direction that they can do no damage if projected by an explosion.

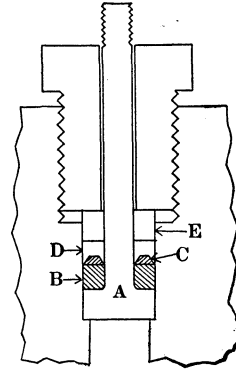


FIGURE 12. The plug for closing holes against high pressures. The plug A is packed with a rubber washer B, a soft steel washer D cupped and filled with solder at C, and the hardened washer E. The scale of the diagram is $\frac{2}{3}$ actual size.

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